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Unusually rapid variability of the GRB000301C optical afterglow *

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Abstract. We present $BVRI$ light curves of the afterglow of GRB000301C, one of the brightest ever detected at a day time scale interval after GRB trigger. The monitoring started 1.5 days after the GRB and ended one month later. Inspection of the extremely well sampled R band light curve and comparison with BVI data has revealed complex behavior, with a long term flux decrease and various short time scale features superimposed. These features are uncommon among other observed afterglows, and might trace either intrinsic variability within the relativistic shock (re-acceleration and re-energization) or inhomogeneities in the medium in which the shock propagates.

Key words: Gamma rays: bursts

1. Introduction

Fundamental progress on the knowledge of Gamma-Ray Bursts (GRBs) has been made possible by detection of their optical counterparts. Of nearly 40 GRBs accurately and rapidly localized so far by BSAX, BATSE/RXTE, IPN, and promptly followed up in the optical, only about 50% exhibited optical afterglows[1], suggesting that these sources are rapidly fading, or heavily obscured. The best monitored afterglows (GRBs 970228, 970508, 980326, 980519, 990123, 990510) exhibit a variety of behaviors, indicating that the shape of the optical decay must be determined not only by the intrinsic physics, but also by the nature, structure and composition of the surrounding medium. Therefore, optical light curves of GRB counterparts need to be frequently sampled for long time intervals, to follow the evolution of the afterglow and to allow mapping the characteristics of the medium.

GRB000301C was detected by the IPN and by the RXTE ASM on 2000 March 1.4 UT with an error box of 50 arcmin^2 (Smith et al. 2000). Its field was acquired starting ~1.5 days later by various optical, infrared and radio telescopes. The optical afterglow was independently detected by Fynbo et al. (2000) and by us (Bernabei et al. 2000a), and is among the brightest ever observed. Near-infrared detection and monitoring of the afterglow are reported in Rhoads & Fruchter (2000). Observations of the counterpart at radio and millimetric wavelengths have been reported by Berger & Frail (2000) and Bertoldi (2000), respectively. Ultraviolet spectroscopy with the STIS instrument onboard HST allowed the determination of the redshift (Smette et al. 2000), then refined by optical ground-based spectroscopy (z = 2.03, Castro et al. 2000). The good sampling and the brightness of the GRB000301C afterglow have allowed a detailed study of its evolution up to 15 days after the explosion. In this paper we present the results of the optical monitoring conducted at Loiano, Calar Alto, Sierra Nevada, Nainital and Canary Islands.

2. Observations and data reduction

Optical $BVRI$ images were collected soon after the notification of the GRB000301C detection, starting ~1.5 days after the high-energy event. Observations were carried out with CCD cameras at the 1.52-meter "G.D. Cassini" telescope of

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* Based on observations collected at the Bologna Astronomical Observatory in Loiano, Italy and at the TNG, Canary Islands, Spain

[1] http://www.aip.de/~jcg/grbgen.html

Table 1. Journal of the optical observations of the GRB000301C afterglow

Exposure start (UT)	Telescope	Filter	Exp. time (minutes)	Seeing (arcsecs)	Magnitude[1]
2000 Mar 2.906	UPSO	R	70	1.4	20.42 ± 0.04[2]
3.144	CAHA	R	5	1.1	20.25 ± 0.05
3.179	CAHA	B	15	1.1	21.07 ± 0.05
3.185	Loiano	R	16.7	2	20.16 ± 0.05
3.205	CAHA	R	5	1.1	20.25 ± 0.05
3.210	CAHA	I	10	1.1	19.94 ± 0.07
3.219	CAHA	V	15	1.1	20.57 ± 0.05
3.232	CAHA	B	15	1.1	21.10 ± 0.12
3.913	UPSO	R	50	1.2	20.51 ± 0.04
4.038	CAHA	R	15	1.6	20.53 ± 0.06
4.149	Loiano	R	36.7	3	> 20.25[3]
4.165	Loiano	B	20	3	> 21.0
5.135	SNO	R	20	2	20.47 ± 0.07
5.152	SNO	B	20	2	21.60 ± 0.20
5.172	SNO	V	20	2	21.04 ± 0.20
5.930	UPSO	R	85	1.3	21.14 ± 0.06
6.135	Loiano	R	30	1.7	21.65 ± 0.20
6.163	Loiano	B	30	1.7	22.45 ± 0.15
6.185	Loiano	I	16.7	1.7	20.82 ± 0.15
6.968	UPSO	R	35	1.6	> 21.6
7.125	Loiano	R	30	1.7	21.68 ± 0.15
7.149	Loiano	B	35	1.7	22.43 ± 0.10
7.177	Loiano	I	20	1.7	21.20 ± 0.15
7.894	UPSO	R	105	1.6	22.00 ± 0.15
8.146	Loiano	R	30	1.6	21.68 ± 0.10
8.170	Loiano	I	30	1.6	21.61 ± 0.10
8.924	UPSO	R	75	1.3	22.04 ± 0.20
Apr 5.213	TNG	B	20	0.5	> 25.5

[1] Magnitudes of the GRB counterpart, not corrected for interstellar absorption
[2] Uncertainties of the magnitudes are at 1σ confidence level; lower limits at 3σ
[3] Note that this measurement is reported as a detection in Bernabei et al. (2000b)

the Bologna University in Loiano, Italy, at the 1.0-meter UPSO telescope in Nainital, India, at the 1.2-meter CAHA telescope in Calar Alto, Spain, at the 1.5-meter telescope of the Sierra Nevada Observatory (SNO) in Granada, Spain, and at the *Telescopio Nazionale Galileo* (TNG) in the Canary Islands, Spain. The complete log of these observations is reported in Table 1.

Images were debiased and flat-fielded with the standard cleaning procedure. Due to the proximity (7 arcsec) of the target to a bright star, we chose to use standard PSF-fitting as our photometric technique, and for this purpose we used the DAOPHOT II image data analysis package PSF-fitting algorithm (Stetson 1987) running within *MIDAS*. A two-dimensional gaussian with two free parameters (the half width at half maxima along x and y coordinates of each frame) was modeled on at least 5 non-saturated bright stars in each image. For each filter, this procedure yields frames magnitude differences among the photometric references of less than 1% in all frames. The errors associated with the measurements reported in Table 1 represent statistical uncertainties (at 1σ), obtained with the standard PSF-fitting procedure. Calibration was done using the $BVRI$ magnitudes of field stars as measured by Henden (2000).

3. Results

In our images we detect a point-like source within the 50 square arcmin error box of the GRB, at the position RA= $16^{\rm h}$ $20^{\rm m}$ $18\overset{\rm s}{.}5$, Dec = 29° $26'$ $35''$ (J2000), consistent with that given by Fynbo et al. (2000). The source variability (see magnitude levels in Table 1) suggests that this is the afterglow of GRB000301C. The light curves in $BVRI$ bands are reported in Fig. 1, where our data are complemented with those published by other authors (Sagar et al. 2000, Jensen et al. 2000, and the GCN circulars archive[2]). Note that some results presented in this paper supersede preliminary values reported in GCNs. Our analysis of UPSO R band data yielded results consistent with those reported by Sagar et al. (2000). No correction has been applied for Galactic extinction, which is anyway small in the

[2] http://gcn.gsfc.nasa.gov/gcn/gcn3_archive.html

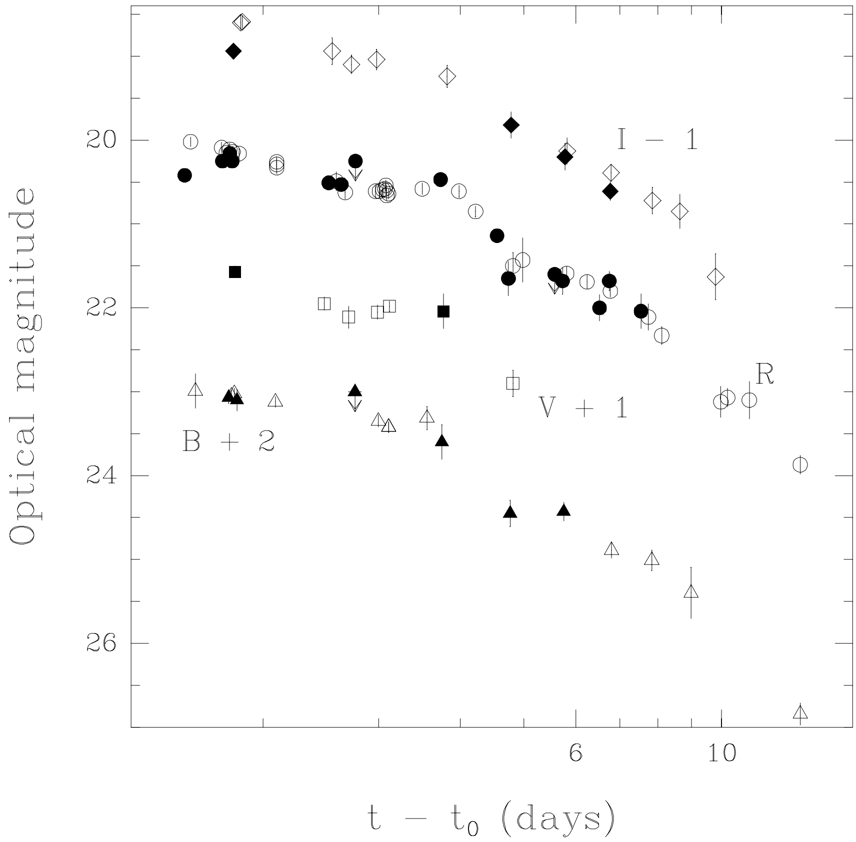

Fig. 1. $BVRI$ light curves of GRB000301C afterglow, based on the data presented in this paper and in the literature (see text). Filled symbols represent data presented in this work, while open symbols refer to measurements published by other authors. We have consistently referred all magnitudes to the calibration zero point of Henden (2000). To the statistical uncertainties a 5% systematic error has been added in quadrature (see text). No Galactic extinction correction, nor host galaxy flux subtraction has been applied. The GRB start time, indicated with t_0, corresponds to 2000 March 1.410845 UT

direction of the GRB ($E(B-V)$ = 0.052, Schlegel et al. 1998); nor has been subtracted any host galaxy continuum emission, this being negligible (Fruchter et al. 2000). A 5% systematic error was added in quadrature to the errors reported in Figs. 1 and 2 to take into account possible photometric discrepancies due to the use of different telescopes and instruments.

The R band light curve, the best sampled, exhibits in its early portion a flaring activity with hour time scale (Fig. 1), with an initial increase (confirmed by S.G. Bhargavi, priv. comm.). The flux then shows a slow decline, lasting about 1.5 days and following approximately a power-law, with a slope $\alpha \sim 0.7$ ($f(t) \propto (t-t_0)^{-\alpha}$, where t_0 is the GRB trigger time). Subsequently the light curve flattens, and an approximately constant, or slightly increasing, behavior is seen till around 3.7 days after the GRB. The flux starts decreasing again thereafter. This decline, which can be fitted by a very steep power-law (index $\alpha \sim 3.5$), levels off around 5 days after the GRB trigger to a "plateau" of two days duration. The flux resumes then the decreasing trend, with a shallower power-law of $\alpha \sim 3$, till the end of the monitoring. The late R band epoch flux and upper limit reported by Fruchter et al. (2000) and Veillet (2000), respectively, are consistent with this trend.

The B band light curve appears well correlated with the R band, though less well sampled. The B band points at 3.5 and 3.7 days after the GRB suggest a variation opposite to that observed simultaneously in the R band. However, the B band variation is not significant and determines only a marginally significant change in the $B-R$ color (Fig. 2a). The B band upper limit determined on April 5 with the TNG is consistent with the power-law decline of the final portion of the light curve.

The fewer V band points show a good correlation of the light curve with that in the R band, with no measurable temporal lag (the $V-R$ color is unchanged, Fig. 2b). In particular, the V band data around 3-4 days after the high-energy event also suggest a local flattening of the light curve.

The I band data confirm the general steepening observed in the other bands, although the second plateau at 5-7 days after the high-energy event is less clearly seen than in the B and R light curves. Also, a rapid flux increase is apparent at the beginning of the I band monitoring, delayed by ∼7 hours with respect to that seen in the R band light curve (see Figs. 1 and 2c).

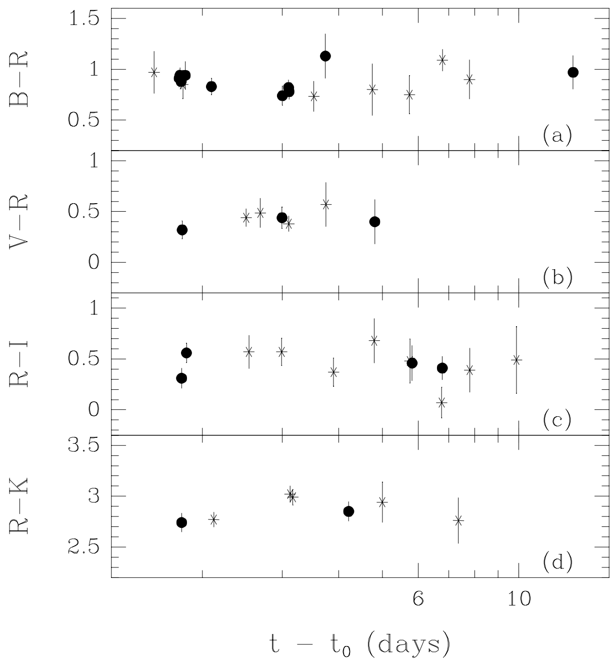

Fig. 2. Colors of GRB000301C afterglow (data are from this paper and from the literature, see text). These are reported as filled circles when computed between pairs of measurements spaced apart in time by no more than 0.5 hr, and as stars when the temporal separation is larger than 0.5 hr, but smaller than 9 hr. As in Fig. 1, calibration by Henden (2000) has been adopted and a 5% systematic error has been added in quadrature (see text). The GRB start time, indicated with t_0, corresponds to 2000 March 1.410845 UT

4. Discussion

Our optical monitoring of the bright GRB000301C afterglow has provided one of the best sampled afterglow datasets, especially in the R filter. The long term behavior of this optical afterglow is better described by a continuous steepening, rather than by a single power-law, as expected in afterglows developing in laterally spreading jets (Sari et al. 1999; Rhoads 1999) or decelerating to non-relativistic regimes (Dai & Lu 1999), and seen in few other cases.

Among equally well monitored GRB afterglows, GR000301C appears peculiar in that several shorter time scale variations are superimposed on the long term decrease. The reality of two of these (3.1-3.7 days and 5-7 days after the event) is supported by their appearance in more than one band. The first two points of the R and I band light curves might suggest a rise and could be reminiscent of the early (1-2 days after the GRB trigger) light curve of GRB970228 and GRB970508 (Guarnieri et al. 1997; Pedersen et al. 1998), although in the latter the initial increase was more structured. In the present case we cannot exclude that the flux is declining since the start of the monitoring, and hour time scale flares modulate this decrease. Some isolated short term variability events are seen in GRB980703 (Vreeswijk et al. 1999) and GRB990123 (Castro-Tirado et al. 1999) and are almost totally absent in GRB990510 (e.g., Stanek et al. 1999).

Recently, various scenarios have been developed in which intrinsic re-energization of the blast wave, or irregularities of the dense interstellar medium in which the blast is expanding can account for the observed behavior (Panaitescu et al. 1998; Mészáros et al. 1998; Sari & Mészáros 2000; Wang & Loeb 2000; Dai & Lu 2000). In particular, a flattening of the afterglow light curve, similar to that exhibited by GRB000301C in the R band on days 3.1-3.7 and 5-7 days after the GRB, is predicted by Kumar & Piran (2000) as a consequence of the collision of a slow shell ejected at a late time after the GRB with an outer shell decelerated by its propagation in the circumburst medium (see their Fig. 5). We note that the temporal occurrence of the observed flattenings could be consistent with a "colliding shells" interpretation, while it is incompatible with the time scale implied by an hypernova scenario (see Rhoads & Fruchter 2000).

The lack of a clear correlation between the R band light curve and the I and K band light curves (see Rhoads & Fruchter 2000 for the latter) might be due to non strict simultaneity of the data points. In fact, the $R-I$ and $R-K$ colors as a function of time show only marginally significant deviations from constancy (Fig. 2c and 2d), and these are mainly exhibited by color values derived from pairs of measurements separated in time by more than 0.5 hours, the shortest variability time scale observed in this afterglow. Our findings underline the critical importance of intensive multiwavelength observations of afterglow sources.

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